

Experimental investigation of CI engine operated Micro-Trigeneration system

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ARTICLE INFO

Article history:

Received 3 August 2009

Accepted 12 February 2010

Available online 26 February 2010

Keywords:

Brake specific fuel consumption

Brake thermal efficiency

Emissions

Trigeneration

Cogeneration

Coefficient of performance

ABSTRACT

A Micro-Trigeneration system based on a CI engine has been designed and realized in laboratory. Experimental investigations have been carried out to evaluate the performance and emissions of the original single generation system and the Trigeneration system developed. Test results of the two generations are also compared. The test results show that the total thermal efficiency of Trigeneration reaches to 86.2% at full load where as it is only 33.7% for original single generation, at the same load. The CO₂ emission from Trigeneration is 0.1211 kg CO₂/kWh compared to that of 0.308 kg CO₂/kWh from single generation at the engine full load. The reduction of CO₂ emission in kg per unit (kWh) of useful energy output is 60.71% compared to that of single generation at full load. The experimental results show that the idea of realizing a Micro-Trigeneration suitable for a small remote home of a developing country like India is feasible and it is very effective technique to utilize the resources efficiently.

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1. Introduction

Growing demand, limited resources, and the negative environmental impacts of mankind's exploitation of energy has emphasized the need to utilize our finite resources wisely. Our common goal is to achieve this task in the most efficient, cost effective, and least polluting manner. Cogeneration and Trigeneration have emerged as the fast growing techniques to increase efficiency and reduce overall emissions. Cogeneration is defined as simultaneous production of power and heat. Trigeneration is simultaneous production of power, heat and cooling or refrigeration. This is also referred as combined cooling, heating and power i.e. CCHP [1,2]. Trigeneration is advantageous over single electricity generation and cogeneration. It has higher total energy efficiency, lower emissions of CO₂ and the other waste gases and it has more choices for useful energy outputs [1–15].

These systems range in size from large units, designed to electrify and heat entire town, to small units, that can serve a single home. In addition to the ability to utilize the by-product heat, Trigeneration also has the advantage of lower transmission losses and increased energy security from natural disasters, over consumption of power and even terrorist acts. Large industrial plants, universities, hospitals, and office buildings have successfully implemented Trigeneration systems. This technology is maturing and typically

utilizes natural gas micro-turbines integrated with adsorption/desiccant coolers to take advantage of by-product heat in warm seasons. The new frontier of Trigeneration is in the residential and small building sector. Applying Trigeneration technology to smaller scale residential and small commercial buildings is an attractive option because of the large potential market. Many manufacturers are developing small-scale Trigeneration systems or micro-CHP units. These small-scale power plants typically range in size from 1 to 15 kWe. These generators utilize an internal combustion engine, Stirling cycle engine or fuel cell as the prime mover. Prime mover drives a generator which produces electrical power. The waste heat from the prime mover is recovered and used to drive thermally activated components such as an absorption chiller or desiccant dehumidifier, and to produce hot water or warm air through the use of heat exchangers.

Several researchers have conducted experimental and simulation based investigations on Trigeneration systems [1–15]. Most of the studies are related to computational simulation techniques or experimental studies on large scale Trigeneration systems [6,7,9,15]. Little work has been done in the field of experimental studies on Micro-Trigeneration systems especially on the systems working on diesel engines of rating capacity below 5 kW. The investigations on such similar systems showed a significant impact on raising the energy efficiency and reducing greenhouse gas emissions responsible for global warming [3,4,8].

The objective of this study was to investigate the feasibility to develop a Micro-Trigeneration system based on a small capacity agricultural engine (3.7 kW) which can serve a small residential home of a village in a developing country like India. Further aim

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Nomenclature

BSFC	brake specific fuel consumption (kg/kWh)
SFC	specific fuel consumption (kg/kWh)
BTE	brake thermal efficiency (%)
CI	compression ignition
CO	carbon monoxide
COP	coefficient of performance
HC	unburned hydrocarbons
HSU	Hartridge smoke unit
NO _x	oxides of nitrogen
kWh	kilo watt hour
Q	heat flow rate (Watt)
UA	multiplication of overall heat transfer coefficient and area of heat transfer
W	Watt

Subscripts

E	evaporator
G	generator in the absorption refrigerator

was to carry out experimentations to investigate the performance and exhaust emissions of the system. The Trigeration system designed and realized in laboratory for the present research work is based on a compression ignition engine. The waste heat from the engine cooling system (run through system in engine block) and engine exhaust system has been utilized to generate hot water through a heat exchanger and cooling or refrigeration through a vapor absorption refrigerator.

2. Experimental setup and procedure

The schematic layout of the experimental setup for the present investigation is shown in Fig. 1. It consists of a test-bed, having a diesel engine, an electric dynamometer, a heat exchanger for heating the water, an exhaust heat driven absorption refrigerator, a fuel tank, an air box, an operation panel having controls and displays for different thermocouples, a tachometer and flow meters. Fuel supply is measured using burette flow meter. NO_x, CO, CO₂ and HC measurements were done with the help of AVL DITEST (AVL DiGas 4000 light) gas analyzer. Envirotech APM 700 Smoke meter was used to measure exhaust smoke. Fig. 2 shows the photograph of the Trigeration system developed in the laboratory.

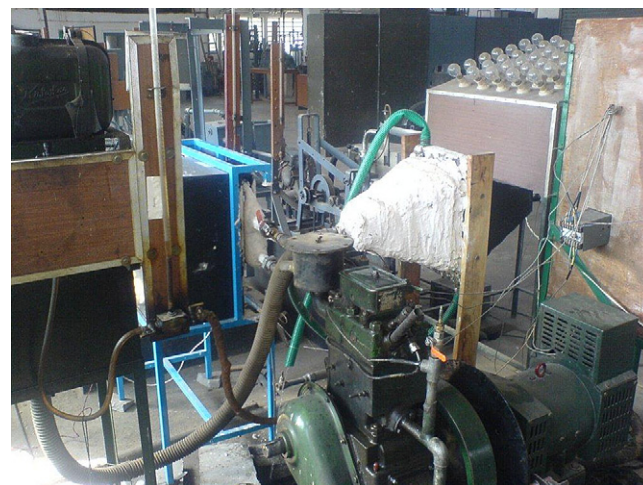


Fig. 2. Photograph of Trigeration test rig realized in the laboratory.

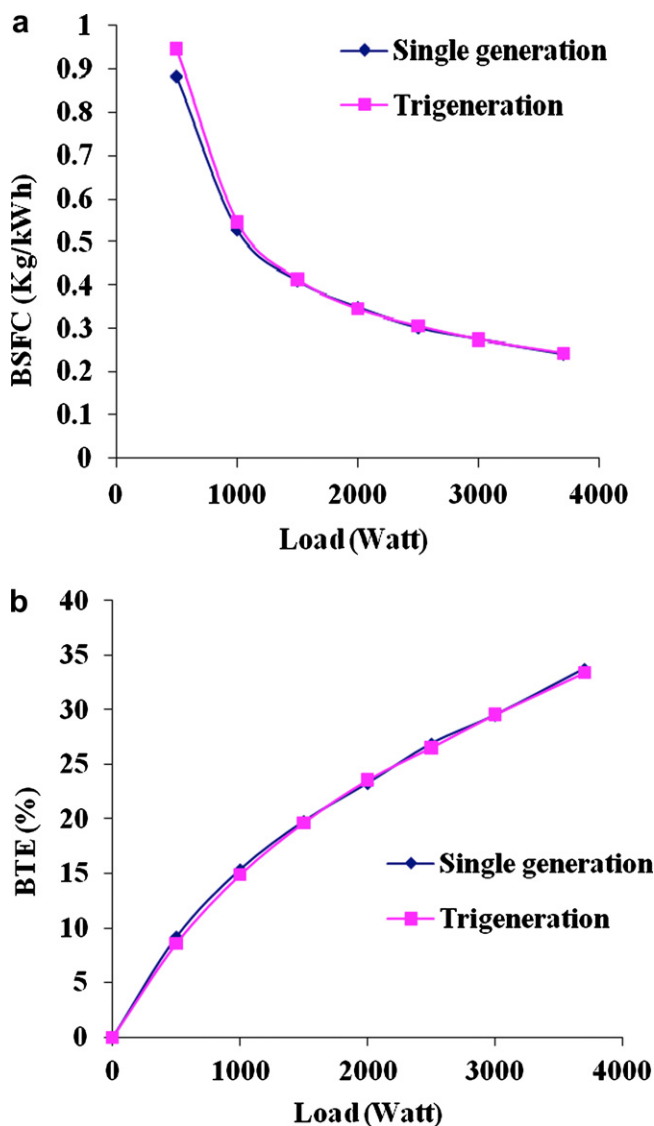


Fig. 3. Variation of (a) BSFC and (b) BTE with engine load and comparison of single generation with Trigeration.

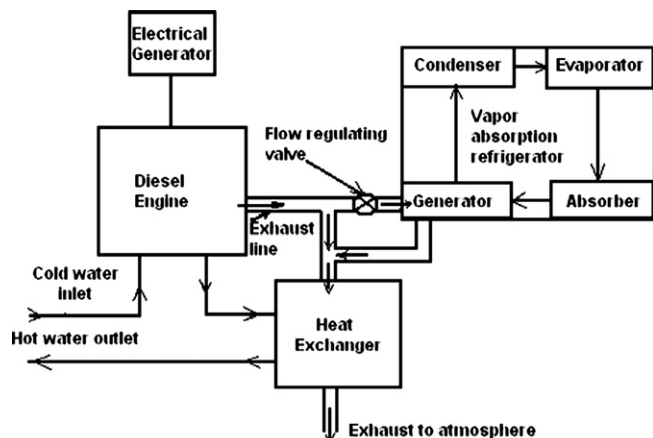


Fig. 1. Schematic layout of Experimental Setup for Trigeration system.

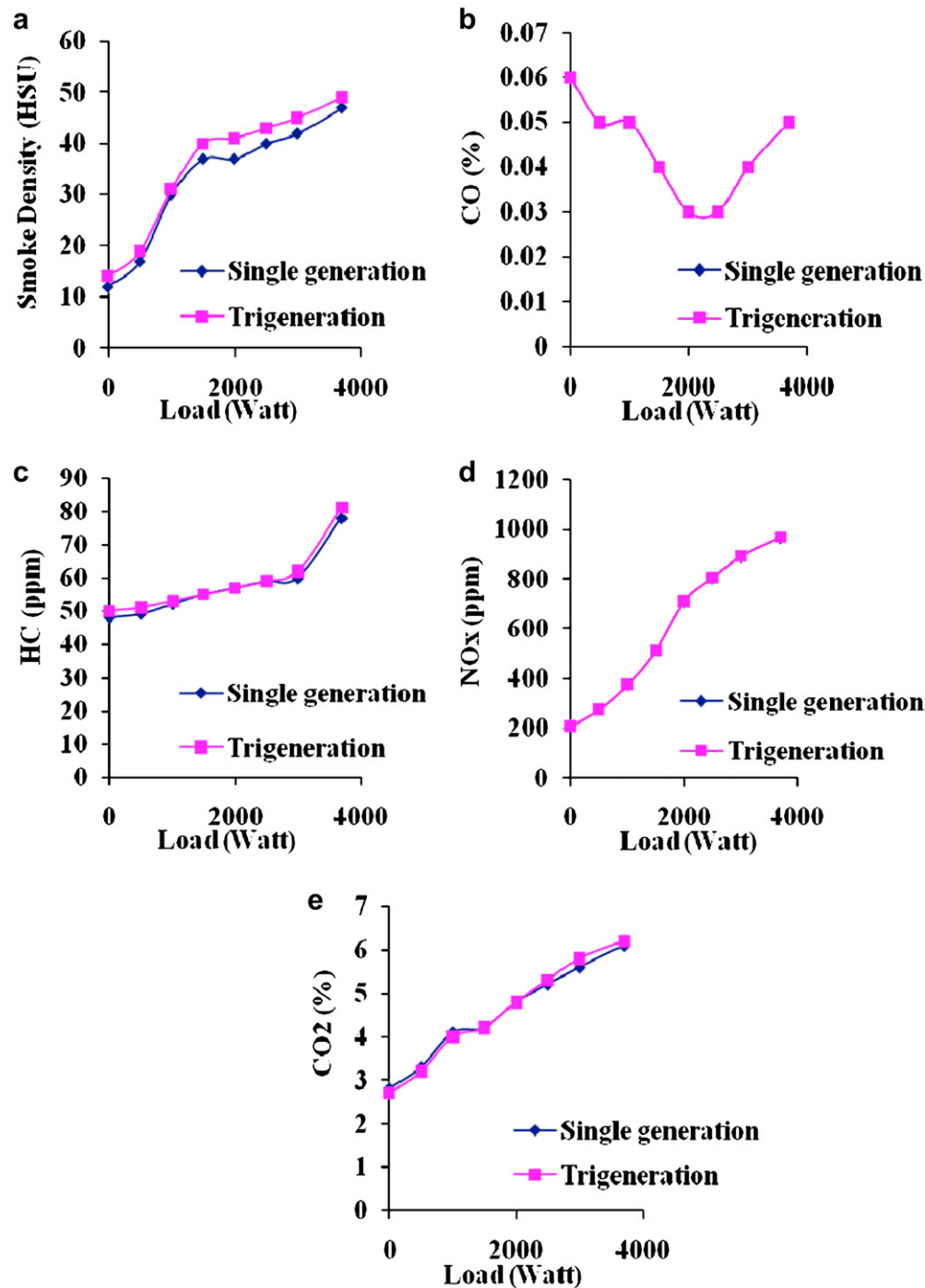


Fig. 4. Variation of (a) Smoke (b) CO (c) HC (d) HC (e) NO_x and (f) CO₂ content in exhaust with engine load and comparison of Single generation with Trigereneration.

2.1. Diesel engine generator set

A typical engine system widely used in the agricultural sector of India has been selected for present experimental investigations. A stationary single cylinder, four stroke, constant speed, water cooled, direct injection Kirloskar make (3.7 kW, Model-AV1) diesel engine with electric generator was used for the experimentations.

2.2. Heat exchanger

A heat exchanger was designed and fabricated for the experimental tests to recover heat from the engine exhaust gas according

to the maximum heat output from the exhaust gases. The heat exchanger is a cross flow, multi-flattened tube and finned, compact, and made of brass tubes and copper fins. The size of the heat exchanger designed was obtained as: Height 0.34 m, Width 0.3 m, Thickness 0.05 m.

2.3. Absorption refrigerator

An Electrolux vapor absorption refrigerator was used for creating the refrigeration effect. It was a commercially available, NH₃–H₂O pair based, electrically operated refrigerator with a capacity of 41 L and heat input of 95 W. Generator of the

refrigerator was modified to utilize the waste heat of exhaust gases. Due to small amount of heat available from the engine, the generator was modified to make the refrigerator, a direct exhaust fired refrigerator instead of a hot water fired or steam fired refrigerator. For the above purpose, a counter flow, double pipe type heat exchanger was designed, fabricated and installed.

2.4. Experimental plan

A plan was designed for the experimental investigation of the performance of the Trigeration system as per following:

2.4.1. Performance of engine generator working on single generation system

A series of tests were designed and conducted to evaluate the engine generator performance when it was to be run on a single generation system. While varying the engine load between idle to full load the relevant data were recorded such as the engine generator power output, fuel consumption, engine exhaust temperature, emissions etc.

2.4.2. Performance of Trigeration

A series of tests were also designed to evaluate the performances of Trigeration. In these tests, the engine load varied between idle to full load (similar to that of single generation) and the required parameters were recorded in order to evaluate the total useful output (power + heat recovered from coolant and exhaust + refrigeration effect), total thermal efficiency etc.

3. Results and discussion

The diesel engine generator system performed satisfactorily on the single generation system and the Trigeration system

mentioned above. There was no engine operational problem during the experimentations. The test results for averaged values of three tests for each parameter are shown in the following sections:

3.1. Engine generator performance and the comparison

The test results for BSFC of engine generator on Single generation and Trigeration systems are shown in Fig. 3(a). The results show that the BSFCs of Single generation and Trigeration are nearly equal. The test results for the brake thermal efficiency of engine generator on Single generation and Trigeration are shown in Fig. 3(b). The test results show that the brake thermal efficiency of engine generator on Single generation and Trigeration are nearly the same. The results show that the integration of the Trigeration components to the engine generator does not influence the performance of the engine generator significantly.

3.2. Engine emissions

The emissions of smoke, CO, HC, NO_x, and CO₂ from the diesel engine on Single generation and Trigeration are shown in Fig. 4. The results show that the differences are almost very small and hence, can be neglected.

3.3. Performance of vapor absorption refrigerator

The parameters of the performance of refrigerator were recorded and evaluated during the Trigeration operation on different engine loads. The test results for the exhaust gas fired refrigerator shows that at the full load, the generator temperature is 115 °C. The final evaporator inlet temperature is −2.9 °C and at food chamber it is 4.3 °C. The heat input to the refrigerator Q_G is 174.2 W; the

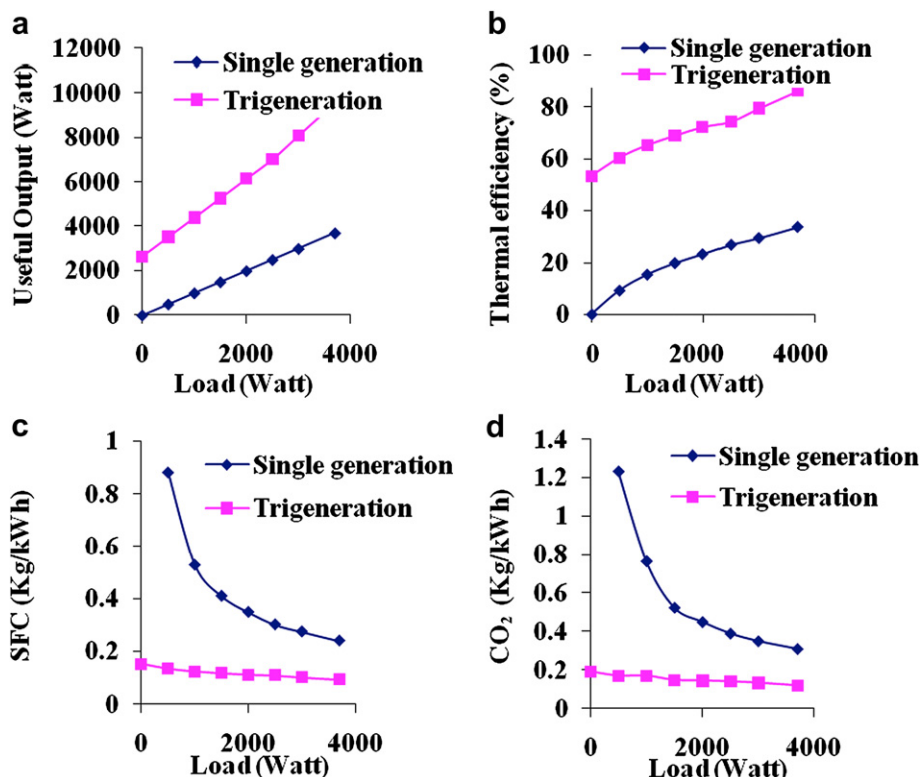


Fig. 5. Variation of (a) Useful energy output (b) Total Thermal efficiency (c) SFC and (d) CO₂ with engine load for Single generation and Trigeration and their comparison.

refrigeration effect Q_E is 40.5 W; and the coefficient of performance of the refrigeration system is 0.2325. The refrigeration effect was calculated by placing a known quantity of water inside the food chamber and noting down the change in temperature of the chamber and time taken by it to reach steady state. The linearity of the fall in temperature was confirmed and UA value for the evaporator chamber was calculated to determine the refrigeration effect.

3.4. Performance of Trigeration system compared to that of single generation system

The values of Trigeration efficiency i.e. Total thermal efficiency of the Trigeration system have been calculated as the ratio of total energy recovered (brake power + heat gain in exhaust and coolant + refrigeration effect) to the heat supplied (lower heating value). The detailed test results of the whole Trigeration system from the engine no load to full load, are shown in Fig. 5. From the figure, it can be seen that

- Useful energy output varies from 2633.4 W at no load to 9571.6 W at full load;
- Total thermal efficiency of Trigeration varies from 53.25% at no load to 86.21% at full load;
- Specific fuel consumption varies from 0.1524 kg/kWh at no load to 0.0941 kg/kWh at full load;
- CO₂ emission varies from 0.1917 kg CO₂/kWh at no load to 0.1211 kg CO₂/kWh at full load.

Fig. 5 also shows the comparisons of the useful energy output, total thermal efficiency, specific fuel consumption and CO₂ emission between Trigeration and single generation. From the results, it is seen that the useful energy output from Trigeration is much higher than that of single generation. The useful energy output of the engine with single generation is only the brake power which is 3700 W at full load. The increase in useful energy output is 158.69% at the full load. The brake thermal efficiency of engine in case of single generation is only 33.7%. The total thermal efficiency of Trigeration is 155.49% higher than that of single generation at full load.

The fuel consumed by Trigeration is much less than that of single generation. The specific fuel consumptions for single generation are from 0.88172 kg/kWh at 500 W load to 0.2406 kg/kWh at full load. The decrease in specific fuel consumption for Trigeration over single generation is 60.86% at full load. The CO₂ emissions for single generation are from 1.234 kg CO₂/kWh at 500 W load to 0.308 kg CO₂/kWh at full load. The CO₂ emission per unit (kWh) of useful energy output of Trigeration is reduced by 60.71% at full load, compared to that of single generation. This shows that the CO₂ emissions from Trigeration are much lower than that from single generation. The test results were validated by comparing it with the test results of experimental study on a small household size Trigeration carried out by Lin Lin et al. [4]. Percentage changes in the values of performance parameters of Trigeration over the single generation for the two studies are quite comparable.

4. Conclusions

In this study, a CI engine operated Micro-Trigeration system has been realized. The performance and emission parameters of the system have been evaluated. When the engine generator runs as a single generation or in a Trigeration, the brake thermal efficiency and the brake specific fuel consumption for the two systems are nearly the same. The increase in useful energy output from the Trigeration as compared to single generation is 158.69% at full load. The total thermal efficiency of Trigeration is 155.49% higher than that of single generation at full load. The decrease in specific fuel consumption for Trigeration over single generation is 60.86% at full load. The CO₂ emission per unit (kWh) of useful energy output from Trigeration is reduced by 60.71% as compared to that from single generation at full load. This research work shows that the idea of realizing a Micro-Trigeration system suitable for a small home of a remote area of developing country like India is feasible and successful. The Trigeration is more efficient, less polluting and more economic than the single generation.

References

- [1] The cogeneration and Trigeration technologies Available from: <http://www.trigeration.com> [accessed 30.01.08].
- [2] Don Pratt, Harold Underwood, Final Design report biodiesel cogeneration project (biocogen report) available at: http://www.messiah.edu/acdept/dephome/engineer/Projects/edr_finalreport/pdf/cogeneration.pdf [accessed 4.02.08].
- [3] M. Denticedaccadia, M. Sasso, S. Sibilio, L. Vanoli, Micro-combined heat and power in residential and light commercial applications. *Applied Thermal Engineering* 23 (2003) 1247–1259.
- [4] Lin Lin, Yaodong Wang, Tarik Al-Shemmeri, Tom Ruxton, Stuart Turner, Shengchuo Zeng, Jincheng Huang, Yunxin He, Xiaodong Huang, An experimental investigation of a household size Trigeration. *Applied Thermal Engineering* 27 (2007) 576–585.
- [5] Nicholas Alexander Stone, "Installation and instrumentation of a micro-CHP demonstration facility" A MS thesis submitted to the Faculty of Mississippi State University, Mississippi State, Mississippi; 2006.
- [6] Piero Colonna, Sandro Gabrielli, Industrial Trigeration using ammonia–water absorption refrigeration systems (AAR). *Applied Thermal Engineering* 23 (4) (2003) 381–396.
- [7] E. Cardona, A. Piacentino, A methodology for sizing a Trigeration plant in Mediterranean areas. *Applied Thermal Engineering* 23 (13) (2003) 1665–1680.
- [8] X.Q. Kong, R.Z. Wang, J.Y. Wu, X.H. Huang, Y. Huangfu, D.W. Wu, Y.X. Xu, Experimental investigation of a micro-combined cooling, heating and power system driven by a gas engine. *International Journal of Refrigeration* 28 (2005) 977–987.
- [9] E. Teopa Calva, M. Picon Nunez, M.A. Rodriguez Toral, Thermal integration of Trigeration systems. *Applied Thermal Engineering* 25 (7) (2005) 973–984.
- [10] J. Bassols, B. Kuckelkorn, J. Langreck, R. Schneider, H. Veelken, Trigeration in the food industry. *Applied Thermal Engineering* 22 (6) (2002) 595–602.
- [11] J. Godefroy, R. Boukhanouf, S. Riffat, Design, testing and mathematical modeling of a small-scale CHP and cooling system (small CHP-ejector Trigeration). *Applied Thermal Engineering* 27 (7) (2007) 68–77.
- [12] R.J. Yadav, R.S. Verma, Effective utilization of waste heat from diesel genset to run air conditioning plant. In: proceedings of national conference on advances in energy research (AER-2006), IIT Bombay; 2006.
- [13] Alam Shah, A proposed Model for utilizing exhaust heat to run Automobile Air-conditioner. In: the second Joint International Conference on "Sustainable Energy and Environment (SEE 2006)" Bangkok, Thailand; 21–23 November 2006.
- [14] R.M. Lazzarin, G.A. Iongo, P.C. Romagnoni, A new HVAC system based on cogeneration by an I.C. engine. *Applied Thermal Engineering* 16 (7) (1996) 551–559.
- [15] C.D. Mone, D.S. Chau, P.E. Phelan, Economic feasibility of combined heat and power and absorption refrigeration with commercially available gas turbines. *Energy Conversion Management* 42 (2001) 1559–1573.